Buoyant Outflows in the Presence of Ccomplex Topography

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LONG-TERM GOALS

The overall goals are closely linked to several ancillary projects. The long term scientific goals are to (a) understand the physical mechanisms that control the exchange between two marginal seas with substantially different water mass characteristics (Aegean Sea and Black Sea) through a complex system of straits (Turkish Straits System); (b) quantify the pathways of the buoyant outflow and evaluate the influence on the dynamics of the receiving coastal areas, as well as on the Mediterranean Sea at large. The long term operational goal is to develop a high resolution numerical model of the Northern Aegean Sea, nested within a coarser Mediterranean Sea model and coupled to a high resolution, unstructured grid model of the Turkish Straits system, which in itself will be coupled to a Black Sea model.

OBJECTIVES

The main *scientific objectives* are to:

a) provide new insights in the understanding of plume dynamics, analyzing the development of a plume that is generated by a buoyant outflow through a narrow strait and its evolution through a topographically complex marginal sea;
b) examine the relative role of buoyancy, wind stress and topography in determining the seasonal and inter-annual variability in the development and evolution of the Dardanelles plume;
c) quantify the transport rates and pathways of the low-salinity waters of Black Sea origin that enter the Aegean Sea (and hence the Mediterranean) through the Dardanelles Strait;
d) study the influence of the flow exchange through the Dardanelles Strait on the Aegean Sea coastal flows, cross-shelf exchanges and basin-wide eddy field;
e) examine if the inter-annual variability of the Dardanelles plume (in the context of changing outflow properties and regional atmospheric forcing) is related to changes in the export of dense waters from the Northern Aegean to the Eastern Mediterranean Sea.

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The main *operational objectives* are to:

f) explore a novel approach in ocean modeling, by developing techniques to parameterize flow exchange through narrow straits that cannot be properly resolved in ocean models;
g) enhance the predictive capability of operational Navy models, by developing and testing a methodology to link the Mediterranean and Black Sea basins that are currently uncoupled in all available global and regional Ocean General Circulation Models;
h) help optimize Navy missions in strategic areas of complex topography;
i) contribute to a prediction tool that is essential for optimizing Navy missions, especially near watersheds and strategic straits.

APPROACH

A high resolution (1/50 degree, ~1.8 km) numerical model has been applied on the Northern Aegean Sea (NAS). The nested model is based on the Hybrid Coordinate Ocean Model (HYCOM; http://hycom.rsmas.miami.edu), to take advantage of the flexible isopycnal-sigma-zlevel coordinate system and advanced mixing schemes, both important factors for the successful simulation of plume dynamics in areas of strong shallow to deep topography transitions, as in the study domain. Boundary conditions have been provided through collaboration with NRL-SSC (A. Wallcraft and B. Kara); a regional Mediterranean Sea HYCOM model (resolution 1/25 degree) has been developed and has been running operationally since 2003 with the Navy Coupled Ocean Data Assimilation (NCODA; Cummings, 2005. For the purposes of this study, a non-assimilative MED-HYCOM simulation has also been executed. Atmospheric forcing Navy products are available to us from NRL: NOGAPS (1 and 1/2 degree) and COAMPS (up to 1/5 degree). Higher resolution products (currently 1/10 degree, evolving to 1/20 degree) are available through collaboration with the Hellenic Center for Marine Research (HCMR). We employ fields from their POSEIDON atmospheric model, http://www.poseidon.hcmr.gr, which is based on SKIRON/ETA forcing, http://forecast.uoa.gr/, but with assimilation of real-time data and on-line coupling of coarse and fine domains (see Papadopoulos et al., 2002).

WORK COMPLETED

Two types of simulations have taken place: process oriented (idealized and/or climatological forcing) and realistic (high frequency forcing). The process oriented simulations have focused on the dynamics of the buoyant discharge and the interaction between the strait and the main topographic features near the discharge site that modify the initial plume evolution (Androulidakis and Kourafalou, 2010). The role of wind stress has been evaluated for periods of persistent northerlies / southerlies which are upwelling / downwelling favorable for the eastern Aegean, respectively. These simulations have elucidated the relative importance of the major circulation forcing mechanisms that govern plume development. Buoy data from the HCMR/Poseidon system are available to us for model evaluation. Trajectories of synthetic floats released at various locations within and outside the Dardanelles buoyant plume have also been computed. Available drifter data (Olson et al., 2007) will be used to compare observed and synthetic float pathways. The data evaluated performance of the NAS-HYCOM model will guide the Dardanelles parameterization choice and will be an important step toward the optimal coupling of the Aegean and Black Seas through the TSS.

RESULTS

River plume dynamics have been studied with the HYCOM model for the first time (Schiller and Kourafalou, 2010) and new parameterization options have been introduced (as included in the latest HYCOM model code release). The physical implications of these parameterizations (lateral and vertical mixing of the buoyant input) have been discussed in detail. An application in the Northern Aegean Sea (Androulidakis and Kourafalou, 2010) employed these options and examined buoyancy-driven flows in the presence of realistic, complex topography. Two significant and novel results have been obtained from the related process oriented studies. First, the outflow of waters of Black Sea origin (BSW) in the Aegean Sea through the Dardanelles Strait was shown to have a significant impact on the basin-wide circulation, with implications on the Aegean water mass characteristics and the formation of eddies and fronts. The role of the complex topographic controls has been elucidated. An important outcome is that the related buoyancy forcing can explain the major circulation features of the N. Aegean, generating the pathways presented in Fig. 1. Process oriented experiments showed that the

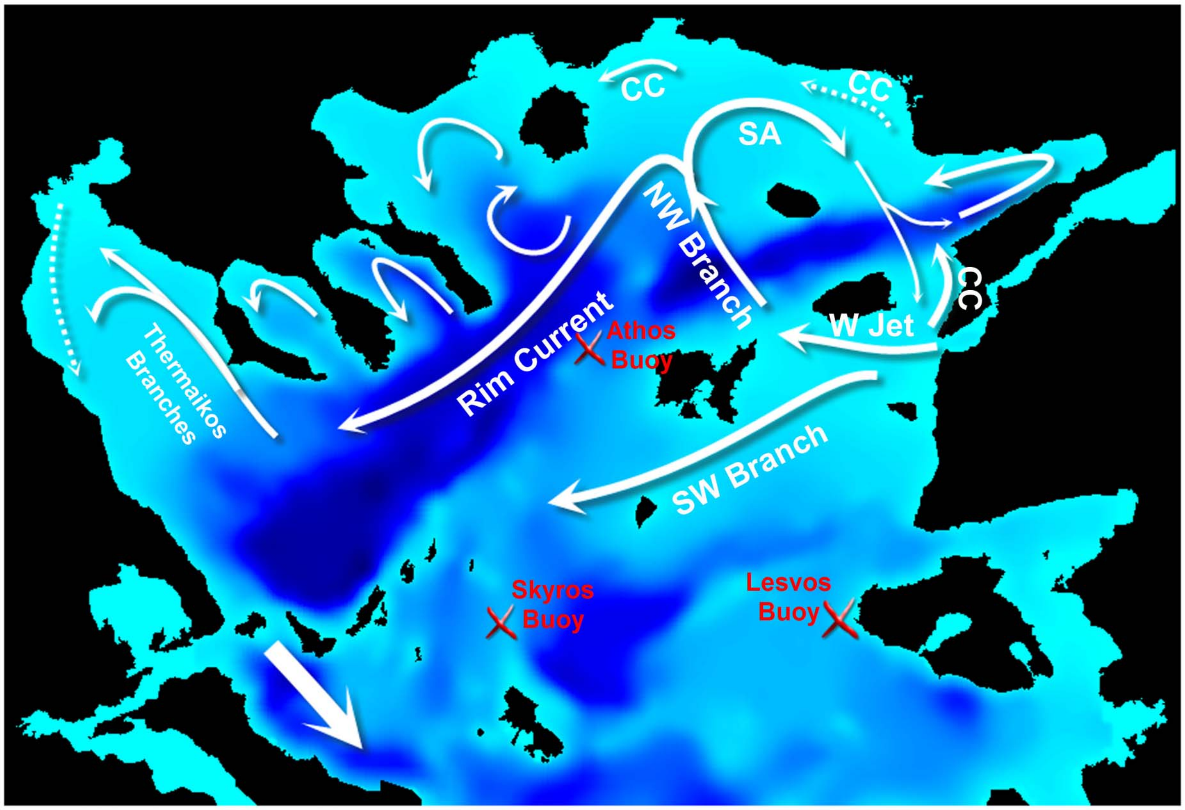


Figure 1. Major North Aegean circulation features related to the BSW plume propagation: the Westward (W) Jet; the South-Westward (SW) Branch; the North-Westward (NW) Branch, feeding into the Samothraki Anticyclone (SA); the Coastal Current (CC) and the Rim Current. Eddy features and intrusions in sub-basins are also marked. The thick arrow shows the direction of BSW induced flow toward the South Aegean, marking the major BSW connectivity pathway with the Eastern Mediterranean. (From Androulidakis and Kourafalou, 2010). Locations of HCMR/Poseidon buoys are marked.

connection and the water transport from the North to the South Aegean and moreover to the East Mediterranean is enhanced by both the southward currents along the west coasts and the direct BSW southward propagation (SW Branch). The NW branch determines the Samothraki Anticyclone, the Rim Current formation and enhances the Coastal Current along the north coasts. It is an important N. Aegean feature delimited by the Limnos-Imroz strait and highly determined by the BSW outflow rate, the upper layer's thickness, the wind state and the formation of the anticyclonic bulge in the vicinity of the outflow mouth.

Second, specific process studies were developed to examine new data findings from the recent (and unprecedented) time series of the outflow rate in the Dardanelles mouth (collaboration with Ewa Jarosz and Bill Teague, NRL-SSC). In particular, the data revealed, for the first time, that an outflow reversal may occur in the Dardanelles mouth, such that the BSW outflow is almost zero and the eastward inflow from the Aegean Sea dominates the entire water column. NAS-HYCOM simulations (Androulidakis and Kourafalou, 2010) showed that such reversals are promoted by specific wind and discharge conditions, namely strong south winds and low outflow rate. In addition, the NAS-HYCOM process oriented model simulations have also been employed to interpret data findings in Kontoyiannis et al., (2003) and Olson et al. (2007). They also substantially extend the numerical studies with climatological forcing in Kourafalou and Barbopoulos (2003); Kourafalou et al. (2003).

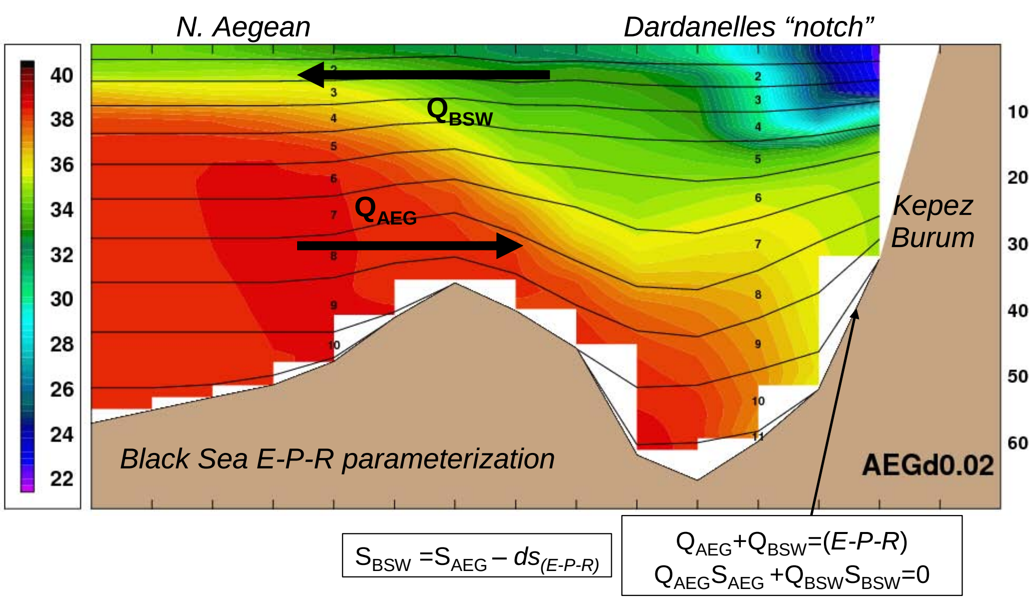


Figure 2 Vertical salinity distribution across the Dardanelles "notch", indicating the major characteristics and assumptions of the Black Sea E-P-R 2-layer outflow exchange parameterization.

An important development has been a new approach in the parameterization of the buoyant outflow from one basin to another through a strait. We have shown that, in the absence of time series of outflow data, realistic variability of outflow properties can be introduced by employing the water budget of the basin that supplies the outflow (using parameters generally available from atmospheric models). In the case of the coupling between the Aegean Sea and the Black Sea through the Dardanelles, all Aegean and Mediterranean models have suffered from great uncertainty in the Dardanelles outflow, as various interpretations of limited historical data, or academic outflow curves

have been in use. We have developed a two layer system based on a methodology suggested by Bryden and Kinder (1991). We have used the E-P-R (Evaporation – Precipitation – Rivers) rate of the Black Sea to calculate the salinity of the upper Dardanelles layer (Fig. 2). High frequency data for the River Danube (which largely controls the variability of buoyancy driven flows in the Black Sea; Tsiaras et al., 2009; Karageorgis et al., 2009) have been employed through a former ancillary project of the PI in the Black Sea. The exchange parameterization is induced at the hydraulic control area ($G_2=F_{AEG}^2+F_{BSW}^2=1 \sim Q_{AEG}=Q_{BSW}$), above the shallowest sill of the Dardanelles Straits (Kepez Burum – easternmost edge of the "notch"). After the validation of the model results with drifter trajectories, *in situ* measurements and satellite data, the E-P parameterization for the Dardanelles outflow has proven more efficient than the use of historical outflow data, because it introduces the Black Sea water budget variability in time. This was found to play a significant role on the upper layer's physical characteristics.

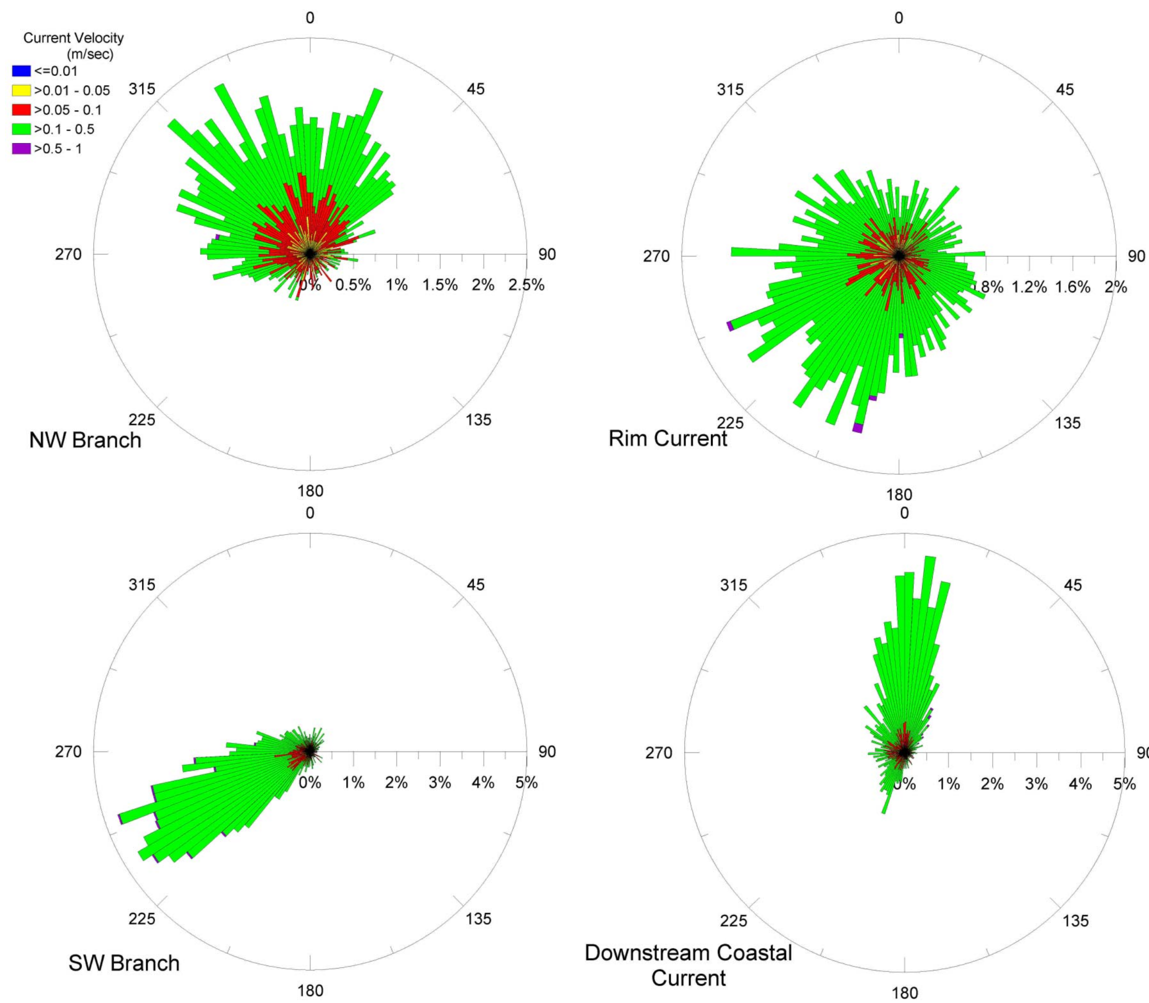


Figure 3 Daily current velocities of the NW Branch (upper-left), the Rim Current (upper-right), the SW Branch (lower-left) and the Downstream Coast current north of the Dardanelles mouth (lower-right) for the period 2002-2008. The colors mark magnitude ranges in m/s: red is 0.01-0.05; green is 0.1-0.5 and purple is 0.5-1.

The 2002-2008 realistic experiments have offered additional insights in the most significant N. Aegean circulation patterns, relative to the BSW outflow. An example of quantifying the major flows and their variability is given in Fig. 3. The NW Branch and the Rim Current show a large spectrum of velocity directions with small occurrence rates (maximum ~ 2%) during the study period of 2002-2008. On the contrary, the SW Branch and the downstream Coastal Current velocities are more concentrated to the southeastward and northward direction respectively, showing higher occurrence rates (maximum ~5%). Additionally, the NW Branch and the Rim Current show more velocities with low magnitude (<0.1 cm/sec) than the other two features, where almost all the velocities are higher than 0.5 cm/sec. Although not frequent, significantly high velocities (>0.5 m/sec) may appear at the Rim Current and at the SW Branch during enhamced north winds that facilitate the formation of these particular features.

An example of model validation with buoy data is given in Fig. 4. The temperature comparison is quite satisfactory, with the model capturing both seasonal and inter-annual variability. The salinity comparison is much more challenging, although the model captures the data defined seasonal trends, deviating during September of 2009. The fall season is particularly variable in salinity at the Skyros basin, as it depends on the BSW pathways that have been shown to follow a cross-basin southwestward route, subject to the variability of the BSW and of the etesian (northerly) winds.

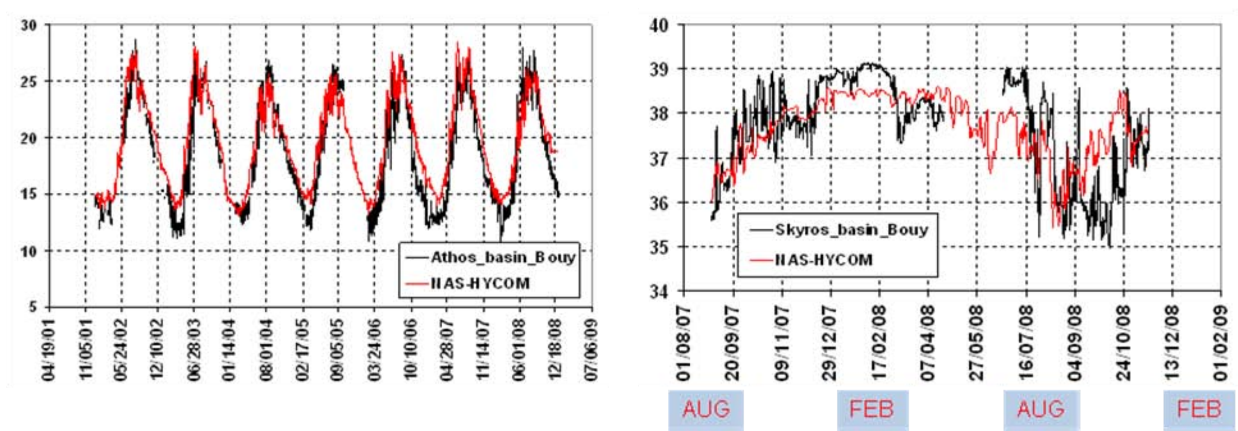
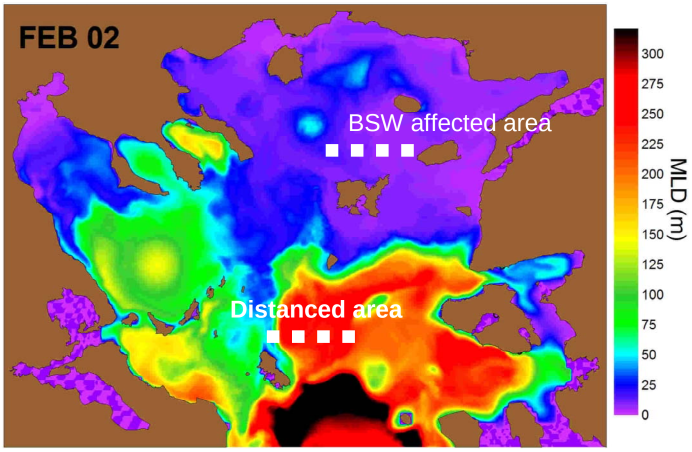


Figure 4. Comparison of NAS-HYCOM (red) and buoy (black) time series of temperature (left, Athos buoy; 2002-2008) and salinity (right, Skyros buoy; 2007-2008); see Fig. 1 for buoy locations.

The 7-year simulation was employed to study dense water formation in the Aegean, which is a major player in recent changes in the eastern Mediterranean decadal variability (Roether et al., 1996; Theocharis et al., 1999). For the first time, the role of low salinity waters from a major buoyant outflow in the pre-conditioning of the basin for dense water formation will be examined. In addition to cold air outbreaks, the existence of the brackish BSW in the N. Aegean also affects the mixed layer and deep water formation (Zervakis et al., 2000; Zervakis et al., 2004). The Mixed Layer Depth (MLD) is large during winter in the south and west areas, while during summer the strong stratification of the column actually eliminates the mixed layer. In areas close to the Dardanelles outflow, covered mostly with BSW, the low air temperatures and the strong wind speeds during winter period play a minor role on the MLD variability. In the areas affected by the BSW, the MLD is significantly lower than in the more distanced areas, where the weather conditions produce strong mixed layers (Fig. 5).

During 2002-2008, two possible dense water formation periods were suggested from the NAS-HYCOM simulations: a) the winter of 2003 and b) the years 2006-2008 (mostly the winter of 2006). The lower temperatures of the entire 7-year simulation were documented (atmospheric data) in winters of 2002-2003 and 2005-2006. Additionally, the 2003-2004 and 2006-2008 years were the driest years of the entire decade. The E-P flux shows positive values in 2003 and again starting in 2006, while the buoyancy loss during 2003 presents its 7-year highest values ($10^{-7}m^2/sec^3$). In all deep basins, a significant rise of the intermediate isopycnals (29-29.11) is observed in both periods and the water volume that was added in the deep isopycnal layers (>29.11 kg/m^3) of the entire area is 0.1 and 0.7 S_v in 2003 and 2006, respectively. The dominant direction of the current at the intermediate layers of Chios Basin (connection to the south Aegean) is southward from 2002 to 2005 and changes to northward from 2006 to 2007, indicating the intrusion of more saline south Aegean waters (modified Levantine Intermediate Water) in the north Aegean that cause a rise on the density of the intermediate water masses. The role of the inter-annual variability in the BSW pathways in the above processes is now being examined.



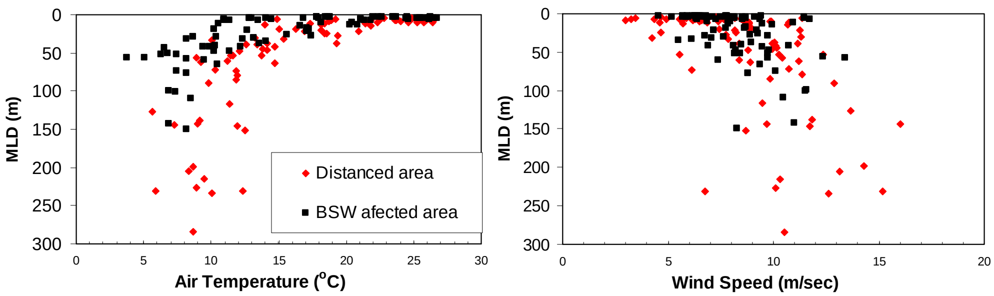


Figure 5. Horizontal distribution of the mean monthly MLD (m) for February 2002 (upper) indicating two N. Aegean areas, one close and one away from the Dardanelles, where the correlation between MLD with air temperature (^oC) (lower-left) and with wind speed (m/sec) (lower-right) is examined.

IMPACT/APPLICATIONS

This study will set the basis for evaluating improvements in the predictability skill of Aegean Sea and Mediterranean Sea models, by developing and evaluating, for the first time, a data based

parameterization of the outflow of waters of Black Sea origin through the Dardanelles Strait. The study findings from numerical simulations and process oriented experiments on the resulting buoyant plume will advance the knowledge on the dynamics that control (a) the exchange of two basins through straits and (b) the transport rates and pathways of the buoyant waters under the influence of high frequency / high resolution atmospheric forcing and in the presence of complex topography. This study will also provide the Aegean Sea model component of a fully coupled Aegean Sea - Turkish Strait System - Black Sea modeling system, which will serve as a Navy prototype for similar areas of marginal seas connected by straits. In addition, the future coupling of the high resolution North Aegean HYCOM model with an unstructured grid model of the TSS and the use of data to evaluate the coupled system will be a valuable benchmark for the modeling of coupled coastal and wetlands models that are critical for optimizing Navy missions. The seasonal and inter-annual variability of the plume controlled salinity distributions will also serve as the basis for the study of biophysical implications, related to the contribution of the eutrophic Black Sea waters on water clarity and productivity of the Northern Aegean Sea. The new options for buoyant lateral forcing in HYCOM will benefit the user community.

RELATED PROJECTS

This study is the ONR funded component of an international effort; the extensive collaboration allows considerable leveraging and data sharing.The University of Miami (UM/RSMAS), the Naval Research Lab (SSC and MRY) and the NATO Undersea Research Center (NURC) have been working closely together to establish the scientific objectives and the collaboration logistics to improve the understanding of inter-basin exchanges through straits. The study area chosen for the development of a comprehensive project that will serve as a baseline for the related scientific objectives is the Turkish Straits System (TSS) and the outflows (Northern Aegean Sea and Western Black Sea). A unique data set is now available from the data campaigns in 2008 and 2009 from NURC (S. Besiktepe) and NRL-SSC (E. Jarosz and B. Teague). In addition, we are collaborating with P.M. Poulain, on the interpretation of the drifter data from NURC and his ONRG-NICOP funded project. Finally, an ancillary project at NRL-SSC (PI C.A. Blain) will utilize these measurements to calibrate a high resolution, unstructured grid model of the TSS, currently under development. If this work continues, the North Aegean model developed in this project will be run as coupled with the TSS model; we have already performed a demonstration of the coupling capabilities. An ancillary European project has been funded by the EU (Integrated Project SESAME: http://www.sesame-ip.eu/); the lead Institute is the Hellenic Center for Marine Research (HCMR). The PI of the project reported herein is an external collaborator of HCMR; leveraged EU funds include Ph.D. student and post-doc support. In addition, data available to us at no cost to ONR include new hydrographic data in the vicinity of the Dardanelles outflow and re-analysis of SeaWiFS imagery for the entire Aegean Sea.

REFERENCES

Androulidakis, Y.S. and V.H. Kourafalou, 2010. Evolution of a buoyant outflow in the presence of complex topography: the Dardanelles plume (North Aegean Sea). *J. Geophys. Res.* (In Review).

Cummings, J.A., 2005. Operational multivariate ocean data assimilation. *Quart. J. Royal Met.Soc.*, 131:3583-3604.

Karageorgis, A.P., V.H. Kourafalou, C. Anagnostou, K.P. Tsiaras, D.E. Raitsos, V. Papadopoulos and A. Papadopoulos, 2009. River induced particle distribution in the Northwestern Black Sea (September 2002 and 2004). *J. Geophys. Res.*, 114, C12003, doi:10.1029/2009JC005460.

Kontoyiannis, H., V. H. Kourafalou and V. Papadopoulos, 2003. The seasonal characteristics of the hydrology and circulation in the Northwest Aegean Sea (Eastern Mediterranean): observations and modeling. *J. Geophys. Res.*, 108, C9, 3302, doi: 10.1029/2001JC001132.
Kourafalou, V.H. and K.A. Barbopoulos, 2003. High resolution simulations on the North Aegean Sea seasonal circulation. *Annales Geophysicae*, 21(1), 251-265.
Kourafalou V.H., K.A. Barbopoulos, K. Tsiaras and J.V. Staneva, 2003. Numerical studies on shelf dynamics: North Aegean Sea and Northwestern Black Sea. In: *"Oceanography of the Eastern Mediterranean and Black Sea."* A. Yilmaz (ed.), Tubitak publ., Ankara, Turkey, pp. 329-334.
Olson, D.B., V.H. Kourafalou, W.H. Johns, G. Samuels and M. Veneziani, 2007. Aegean Surface Circulation from a Satellite-tracked Drifter Array. *J. Phys. Oceanogr*., 37(7), pp. 1898-1917.
Papadopoulos A., G. Kallos, P. Katsafados, and S. Nickovic, 2002: "The Poseidon weather forecasting system: An overview". *The Global Atmosphere and Ocean Systems*, 8, No. 2-3, 219-237 (retitled *Journal of Atmospheric and Ocean Science*).
Roether W, B. Manca, B. Klein, D. Bregant, D. Georgopoulos, V. Beitzel, V. Kovacevic and A. Luchetta, 1996. Recent changes in eastern Mediterranean deep waters. Science 271: 333–335.
Schiller, R.V. and V.H. Kourafalou, 2010. Modeling river plume dynamics with the Hybrid Coordinate Ocean Model. *Ocean Modeling*, doi:10.1016/j.ocemod.2009.12.005.
Theocharis A, K. Nittis, H. Kontoyiannis, E. Papageorgiou and E. Balopoulos, 1999. Climatic changes in the Aegean Sea influence the eastern Mediterranean thermohaline circulation (1986–1997). *Geophys. Res. Lett.*, 26(11): 1617–1620.
Tsiaras, K., V.H. Kourafalou, A. Davidov and J. Staneva, 2008. A three-dimensional coupled model of the western Black Sea plankton dynamics: seasonal variability and comparison to SeaWiFs data. *J. Geophys. Res*, 113, C07007, doi:10.1029/2006JC003959.
Zervakis, V., D. Georgopoulos and P. G. Drakopoulos, 2000. The role of the North Aegean in triggering the recent Eastern Mediterranean climate changes. *J. Geophys. Res*., 105, 26,103-26,116.
Zervakis V, Georgopoulos D, A.P. Karageorgis and A. Theocharis. 2004. On the response of the Aegean Sea to climatic variability: a review, Int. J. Climatol. 24, 1845–1858.

PUBLICATIONS

Schiller, R.V. and V.H. Kourafalou, 2010. Modeling river plume dynamics with the Hybrid Coordinate Ocean Model. *Ocean Modeling*, doi:10.1016/j.ocemod.2009.12.005.
Androulidakis, Y.S. and V.H. Kourafalou, 2010. Evolution of a buoyant outflow in the presence of complex topography: the Dardanelles plume (North Aegean Sea). *J. Geophys. Res.* (In Review).
Karageorgis, A.P., V.H. Kourafalou, C. Anagnostou, K.P. Tsiaras, D.E. Raitsos, V. Papadopoulos and A. Papadopoulos, 2009. River induced particle distribution in the Northwestern Black Sea (September 2002 and 2004). *J. Geophys. Res.*, 114, C12003, doi:10.1029/2009JC005460.
Blain, C.A., M.K. Cambazoglu and V.H. Kourafalou, 2010. Modeling the Dardanelles Strait Outflow Plume using a Coupled Model System. Proceedings of the Marine Technology Society Conference MTS/IEEE *Oceans09: Marine Technology for our Future: Global and Local Challenges*, ISBN: 978-1-4244-4960-6, INSPEC Accession Number: 11155249, Biloxi, MS, 8 pp.
Androulidakis, Y.S., V.H. Kourafalou, A. Wallcraft, C.A. Blain, D. Raitsos and K. Tsiaras, 2010. Buoyant outflow pathways connecting basins through straits: a multi-nested approach. *Eos Trans. AGU, 91(26), Ocean Sci. Meet. Suppl.*, Abstract PO35A-05.

Kourafalou, V.H., Y.S. Androulidakis, and Y.N. Krestenitis, 2010. Investigating the circulation impacts of the Dardanelles flow exchange with the North Aegean Hybrid Coordinate Ocean Model. *Proceedings of the 39th CIESM Congress,* published by the Mediterranean Science Commission (In Press).

Kourafalou, V.H., K. Tsiaras, D. Raitsos and Y.S. Androulidakis, 2010. Advances in the Northeastern Mediterranean Sea: complex pathways of the waters of Black Sea origin through the Aegean Sea. *Proceedings of the 39th CIESM Congress*, published by the Mediterranean Science Commission (In Press).